3. CHARACTERIZATIONS OF MOFs
3.0 Types of Microstructured Optical Fibres

Micro structured optical fibers [MOFs] constitute a new class of photonic crystal waveguides, formed by introducing a high-index defect (or a missing hole) in a regular triangular (or hexagonal) photonic crystal (PC) array of air holes along the propagation direction of the waveguide. They are also called Photonic crystal fibres [PCF] or Holey fibres [HF] or Air hole Assisted Fibres [AHAF].

There are basically two main types of MOFs [a] air-guiding [Hollow Core HCMOF] which guides light via a Photonic Band-Gap effect [PBG] and [b] index-guiding [IGMOMF] which guides via a modified total internal reflection mechanism [MTIR]. In air-guided MOF, the core is hollow, and light is guided by the photonic band gap (PBG) effect, a mechanism that does not require a higher refractive index in the core in order to confine and guide light. The PBG guidance effect relies on coherent backscattering of light into the core. In index-guided MOFs the core area is solid and the light is confined to a central core as in conventional fibers. [Fig 3.01]

MOFs in simplest form use a single dielectric base material (with dielectric function \(\varepsilon_b = n_b^2\)) and for the majority of fabricated fibres silica has been the most common choice. This preference has of course been highly motivated by silica’s transparency in the visible to infrared
regimes. But the choice has also been strongly driven by the highly matured glass technology used in the fabrication of standard telecommunication fibres. However, a growing interest in fibre optics for other wavelengths and light sources has recently led to a renewed interest in other base materials including chalcogenide glass\textsuperscript{[72]}, lead silicate glass, telluride glass, bismuth glass, silver halide, Teflon, and plastics/polymers.

One of the most appealing features of MOFs is their high flexibility based on the particular geometry of their refractive index distribution. The transverse section of a MOF is a two-dimensional (2D) silica-air photonic crystal in which an irregularity of the refractive index, or defect, is generated. In MOFs guidance occurs in the region where the defect is located, which determines an effective MOF core. Analogously, one can define an effective MOF cladding constituted by the region surrounding the core, or defect area that has the form of a perfectly periodic 2D photonic crystal. As compared to conventional fibers, it is apparent that MOFs enjoy a more complex geometrical structure because of their 2D photonic crystal cladding. This fact allows us to manipulate the geometrical parameters of the fiber (e.g., the air-hole radius $a$, [dia d] and the lattice period, or pitch, $\Lambda$ of a 2D triangular photonic crystal cladding) to generate an enormous variety of different configurations\textsuperscript{[39]}.

The peculiarities of the guidance in the core depend on the nature of the defect, which can generate donor or acceptor guided modes by an analogous mechanism leading to impurity states in electronic crystals. On the other hand, the functional form of the dispersion relation of guided modes is very sensitive to the 2D photonic crystal cladding. For this reason, it is easy to control, to some extent, the dispersion properties of guided modes by manipulating the geometry of the photonic crystal cladding.

Unlike the conventional Single Mode Fibers [SMF], the effective cladding index of the MOFs is a strong function of $\lambda$, the wavelength, and the modes supported by the waveguides are generally more dispersive. For this reason, MOFs have some unique properties that cannot be achieved in conventional fibers, such as [a] single-mode operation at a wide wavelength range, [b] highly tunable dispersion, and [c] highly controllable mode effective areas for linear and nonlinear applications etc.
Because of its unique properties and ease of fabrication, MOFs can be made from a number of optical materials, such as silica and polymer; and they have many potential applications such as dispersion-related fibers, Supercontinuum generation, and large mode effective area fibers. The optical properties of MOFs can be further easily controlled by filling the air holes with thermo-sensitive material.

3.1 Theory and Operation Principle

In this section, the operation principle and unique modal characteristics of MOFs are described. Some basic design considerations and performance parameters for MOFs are also mentioned. Figure 3.02 [a] shows the transverse cross-section of a typical MOF that consists of a central high index defect (or a missing hole) in a regular triangular (or hexagonal) array of air holes. Except the number \( N \) of rings of air holes, there are two main design parameters, namely, the air hole diameter \( d \) and the pitch \( \Lambda \).

Fig 3.02 [b][48] shows the actual image of a manufactured MOF. Like conventional step index fibers, the operation principle for MOFs is to guide light by the Total Internal Reflection (TIR). Another similarity between step index fibers and MOFs is that the effective refractive index in the area around the core is lower than that of the core itself. For HCMOF however it will be Photonic bandgap guidance.

There are several methods that can be used to analyze the modal characteristics of MOFs. There are however two basic classes of methods:

- Analytical and semi-analytical methods, such as the Effective Index Method (EIM), the Envelope Approximation Method (EAM), and the modal expansion methods (for example, the Plane Wave Expansion method, or PWE)
- Numerical methods, such as the Finite Difference Method (FDM), the Finite Element Method (FEM), and the Finite Difference Time Domain method (FDTD).
Fig 3.02 [a] Transverse cross section with parameters of a typical MOF

Fig 3.02[b] Structure and dimensions of a HCMOF [Courtesy Photonics research centre]
From the band structure of the Microstructured cladding, the effective index $n_{\text{fsm1}}$ of the lowest band (also called the Fundamental Space Filling Mode or SFM1), which is a strong function of wavelength, can be calculated. Therefore, for the guided modes, their corresponding effective indices $n_{\text{eff}}$ meet the following relation:

\[ n_{c} > n_{\text{eff}} > n_{\text{fsm1}} \]  \[ 3.1 \]

Where $n_{c}$ is the refractive index of the core of the waveguide (for example, pure silica) and $n_{\text{fsm1}}$ is the cladding effective index of the MOF. In order to use the modal properties of conventional step index fibers, the normalized effective frequency $V_{\text{eff}}$, less than 2.405 for the single mode operation, is defined as:

\[ V_{\text{eff}} = \frac{2\pi}{\lambda} a_{\text{eff}} \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2} \]  \[ 3.2 \]

where $a_{\text{eff}}$ is the equivalent core radius of MOFs and $\lambda$ is the operating wavelength. It is worth noting:

- that the range of the equivalent core radius $a_{\text{eff}}$ could be selected from $\Lambda/2$ to $\Lambda$ where $\Lambda$ is the pitch of MOFs.
- because the cladding effective index has a strong wavelength dependence, the equivalent core radius $a_{\text{eff}}$ is another variable that depends on the wavelength and design parameters of MOFs.

Overall, however, the operation principle of MOFs is based on the TIR effect. For sake of simplicity, the regular circular MOF with one missing hole, as shown in Figure 3.01, is used as the main example in this application note. However, more complicated MOFs (for example, those that have interstitial holes, oval shapes for polarization-maintaining fibers, or more missing holes) can be designed following the same process.
3.2 Performance Parameters

![Cross section of a triangular MOF](image)

**Fig 3.03 Cross section of a triangular MOF**

The main parameters for the MOF include the propagation constant, loss, group delay, dispersion, effective area, and modal diameters. All of these properties are related to the fibre design, namely, the pitch ($\Lambda$) of the periodic array, the holes radius ($d$) and the number ($N$) of rings around the core. The optimization of MOF design is often difficult due to the fact that the optical properties do not usually vary in a simple way with the fibre geometry parameters.

This difficulty increases exponentially with the numbers of variables of the problems ($\Lambda$, $N$, different $d$ and different materials that can be allowed in the same structure etc…) and with the number of properties that have to be considered (chromatic dispersion, slope of this dispersion, confinement losses, non linearity etc…). The design optimization is mostly performed by trial and test approach [39]. This is a time consuming approach, both for the computer and the designer who has to interact regularly with the output of the calculation to design a new test fibre.
3.3 Basic Design Considerations

When the operation principle of MOFs and the relevant performance parameters for the materials to be used (for example, silica or polymer) have been understood, and the design requirements (for example, single mode operation and dispersion) are frozen, a designer can apply analytical and numerical solvers to design MOFs.

3.4 Analysis Methods

In order to understand and fabricate effective MOFs, both analytical and numerical methods should be used to predict accurate modal properties. For example, EIM treats the MOF as a waveguide in which a silica core (or defect) is surrounded by a uniform cladding with a lower effective index, which can be related to the band structure of the photonic crystal in absence of the core. In other words, the main task in EIM is to calculate the effective index of the Photonic Crystal [PC] cladding associated with the space-filling modes [6].

It is simple and intuitive and the modal properties of the MOF can be solved by conventional waveguide theory as long as the effective cladding index is obtained. However, due to the inherent assumption that the photonic crystal structure is extended to infinity, the effects of the finite number of the rings and special shapes of the MOF cannot be accounted for. Fortunately, all of these issues are addressed by numerical methods [37, 38]. However, numerical simulations are, in general, time-consuming and costly.

An analytical approach based on the V parameter (normalized frequency) frequently used in the design of conventional optical fibers has been developed for index-guiding MOFs. By appropriately defining the V parameter, various unique properties of MOFs can be qualitatively understood within the framework of well established classical fiber theories without heavy numerical computations. Although the V parameter offers a simple way to design a MOF, a limiting factor is that a numerical method is still required for obtaining the accurate effective cladding index. If we can get empirical relations for not only V parameter but also W parameter (normalized transverse attenuation constant) only dependent on the wavelength and the structural parameters, they would be very useful for simple design of MOFs. The aim here now is to provide the empirical relations for V parameter and W parameter of MOFs based on the
fundamental geometrical parameters – the air hole diameter and the hole pitch. Through the empirical relations we can easily evaluate the fundamental properties of MOFs without the need for numerical computations.

3.5. The V Parameter Expression

We consider a MOF with a triangular lattice of holes as shown in Fig. 3.03, where \( d \) is the hole diameter, \( \Lambda \) is the hole pitch, and the refractive index of silica is 1.45\(^{48}\). In the center an air hole is omitted creating a central high index defect serving as the fiber core. For this MOF, V parameter is given by

\[
V = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{c0}^2 - n_{FSM}^2} = \sqrt{U^2 + W^2}
\]

\[
U = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{c0}^2 - n_{eff}^2}
\]

\[
W = \frac{2\pi}{\lambda} a_{eff} \sqrt{n_{eff}^2 - n_{FSM}^2}
\]

where \( \lambda \) is the operating wavelength, \( n_{c0} \) is the core index, \( n_{FSM} \) is the cladding index, defined as the effective index of the so-called fundamental space-filling mode in the triangular air hole Lattice, \( n_{eff} \) is the effective index of the fundamental guided mode, and \( a_{eff} \) is the effective core radius that here is assumed to be \( \Lambda/\sqrt{3} \). The parameters U and W are called, respectively, the normalized transverse phase and attenuation constants. Established and published works under reference\(^{9}\) proposed the following effective V parameter for triangular MOFs:

\[
V_{eff} = \frac{2\pi}{\lambda} \sqrt{n_{eff}^2 - n_{FSM}^2}
\]

and reported the empirical relation for \( V_{eff} \) of Eq. (3.6). However, this definition is intrinsically different from the original V parameter definition in step-index fiber (SIF) theory and corresponds to the W parameter. Therefore it seems to be difficult to apply the design
principle of SIFs straightforwardly to MOFs. So we adopt the \( V \) parameter definition of Eq. (3.3).

One can estimate the fundamental properties of MOFs using the \( V \) parameter in Eq. (3.3). However a limiting factor for using Eq. (3.3) is that a numerical method is still required for obtaining the accurate effective cladding index \( n_{fsm} \).

Figure 3.04 shows \( V \) values calculated through trial and error method described below from established works \(^{[9]}\) of vector FEM\(^{[8]}\) as a function of \( \lambda/\Lambda \) for \( d/\Lambda \) ranging from 0.20 to 0.80 in steps of 0.05. By trial and error, data set of FEM can be fitted to a function of the form

\[
V \left( \frac{\lambda}{\Lambda}, \frac{d}{\Lambda} \right) = A_1 + \frac{A_2}{1 + A_3 \exp(A_4\lambda / \Lambda)} \tag{3.7}
\]

and the results are indicated by the curves. For accurate fitting, the data sets are truncated at \( V = 0.85 \). In Eq. (3.7) the fitting parameters \( A_i \) (\( i = 1 \) to 4) depend on \( d/\Lambda \) only. The data are well described by the following expression

\[
A_i = a_{i0} + a_{i1} \left( \frac{d}{\Lambda} \right)^{b_{i1}} + a_{i2} \left( \frac{d}{\Lambda} \right)^{b_{i2}} + a_{i3} \left( \frac{d}{\Lambda} \right)^{b_{i3}} \tag{3.8}
\]

and the coefficients \( a_{i0} \) to \( a_{i3} \) and \( b_{i1} \) to \( b_{i3} \) are given in Table 3.1. For \( \lambda/\Lambda < 2 \) and \( V > 0.85 \) the expression of Eq. (3.7) gives values of \( V \) which deviates less than 1.3% from the corrected values obtained from Eq. (3.3).

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**Table 3.1** Fitting coefficients of equation 3.8
Using the effective $V$ parameter in Eq. (3.7), the effective cladding index $n_{\text{fsm}}$ can be obtained without the need for numerical computations. Figure 3.06b] shows $n_{\text{fsm}}$ as a function of $\lambda/\Lambda$ for $d/\Lambda$ ranging from 0.2 to 0.8 in steps of 0.1. The expression of Eq. (3.7) gives values of $n_{\text{fsm}}$ which deviates less than 0.25% from the values obtained through vector FEM for $\lambda/\Lambda<1.5$ and $V>0.85$ from works under reference.

From Eq. (3.7) the cutoff condition is given by $V=2.405$, as in conventional SIFs. Using the empirical relation of Eq. (3.7) and various formulas in terms of the $V$ parameter found for SIFs, one can easily estimate the fundamental properties of MOFs, such as mode field diameter, beam divergence, splice loss, and so on.

### 3.6 The W Parameter Expression

In the previous section we provided the empirical relation for the $V$ parameter of MOFs. Using Eq. (3.7) one can easily obtain the effective cladding index $n_{\text{fsm}}$. However, one usually needs heavy numerical computations to obtain the accurate values of $n_{\text{eff}}$ in Eq. (3.5). It would be more convenient to have an empirical relation for the $W$ parameter of MOFs. Published works under reference [9] have reported the empirical relations for the $W$ parameter; however, one cannot obtain the value of $n_{\text{eff}}$ from the $W$ parameter only. In order to obtain $n_{\text{eff}}$, one needs the empirical relations for both the $V$ and $W$ parameters.

Figure 3.05 shows $W$ values calculated from Matlab programs through trial and error method as a function of $\lambda/\Lambda$ for $d/\Lambda$ ranging from 0.20 to 0.80 in steps of 0.05. The basis is reported works of vector FEM [38]. By trial and error each data set in Vector FEM can be fitted to the same function in Eq. (3.7) as

$$ W\left(\frac{\lambda}{\Lambda}, \frac{d}{\Lambda}\right) = B_1 + \frac{B_2}{1 + B_3 \exp(B_4 \lambda/\Lambda)} $$

(3.9)

and the results are indicated by the solid curves. For accurate fitting, the data sets are truncated at $W = 0.1$. In Eq. (3.9) the fitting parameters $B_i$ ($i = 1$ to 4) depend on $d/\Lambda$ only.
The data are well described by the following expression

$$B_i = c_{i0} + c_{i1} \left( \frac{d}{\lambda} \right)^{di1} + c_{i2} \left( \frac{d}{\lambda} \right)^{di2} + c_{i3} \left( \frac{d}{\lambda} \right)^{di3} \quad (3.10)$$

and the coefficients $c_{i0}$ to $c_{i3}$ and $d_{i1}$ to $d_{i3}$ are given in Table 2.2. For $\lambda/\Lambda < 2$ and $W > 0.1$ the expression of Eq. (3.9) gives values of $W$ which deviates less than 0.015 from the corrected values obtained from Eq. (3.5).

<table>
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<td>24.8</td>
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</tr>
</tbody>
</table>

**Table 3.2 Fitting coefficients of equation 3.10**

Using the $V$ parameter in Eq. (3.7) and the $W$ parameter in Eq. (3.9), the effective index of the fundamental mode $n_{eff}$ can be obtained without the need for numerical computations. Figure 3.06 [b] shows $n_{eff}$ as a function of $\lambda/\Lambda$ for $d/\Lambda$ ranging from 0.2 to 0.8 in steps of 0.1, where the curves show the results from Eqs. (3.3), (3.5), (3.7), and (3.9) with $a_{eff} = \Lambda/\sqrt{3}$. For $\lambda/\Lambda < 1.5$ and $W > 0.1$ the expressions of Eqs. (3.5) and (3.7) give values of $n_{eff}$ which deviates less than 0.15% approximately from the values obtained through vector FEM [8, 9].

### 3.7 Endlessly Single Mode Criterion

The term endlessly single-mode (ESM) refers to MOFs which regardless of wavelength only
support the two degenerate polarization states of the fundamental mode. In the framework of the \( V \)-parameter this corresponds to structures for which \( V_{MOF} < \pi \) for any \( \lambda / \Lambda \).

Equation [3.7] when \( \lambda \to 0 \) \( V_{MOF} \to \pi \)

\[
V \left( \frac{\lambda}{\Lambda}, \frac{d}{\Lambda} \right) = A_1 + \frac{A_2}{1 + A_3 \exp(A_4 \lambda / \Lambda)} \to \pi \text{ when } \lambda \to 0 \quad [3.11]
\]

In particular MOFs are endlessly single-mode for \( d/\Lambda \leq 0.42 \) irrespectively of the base material.

Physically, this property of holey fibers depends upon the fact that the degree of light-filling of air holes in the cladding of holey fibers varies as the radiation wavelength changes. As a result, the difference in the refractive indices of the fiber core and the fiber cladding becomes wavelength dependent, considerably expanding the spectral range of single-mode guiding\(^{73}\).

In the limiting case when the radiation wavelength \( \lambda \) is much greater than the pitch \( \Lambda \) of the structure, the effective refractive index of the cladding, \( n_{clad} \), is equal with a high accuracy to the weighted-mean of the refractive indices of glass and air in the structure. As the wavelength \( \lambda \) decreases, light becomes mainly concentrated in the regions with a higher refractive index.

This qualitative analysis explains why light with a shorter wavelength `sees' more glass and less air. Thus, as the radiation wavelength becomes shorter, the difference between the refractive index of the fiber core and the effective refractive index of the fiber cladding decreases, which allows the single mode criterion to be met over a sufficiently broad wavelength range.
Fig 3.04. V parameter as a function of normalized $\lambda$ with pitch [Matlab]
Fig 3.05 W parameter as a function of normalized $\lambda$ with pitch [Matlab]
Fig 3.06 [a] Effective Cladding index as a function of $\lambda$ and pitch [Matlab]
Fig 3.06[b] $n_{eff}$ of fundamental mode as a function of $\lambda$ and pitch [Matlab]
3.8 Loss Mechanisms

The most important factor for any optical fibre technology is loss. Losses in Conventional optical fibres have been reduced to near theoretical minimum over the last three decades. The minimum loss in fused silica is around 1550 nm, and is less than 0.2 dB/km. This limit sets the amplifier spacing in long-haul communications systems. Loss mechanisms in MOFs are here described in details, in order to understand how far the technology can go to reduce their values.

The optical loss $\alpha_{dB}$, [dB/km], of MOFs with a sufficiently reduced Confinement loss, can be expressed as

$$\alpha_{dB} = A/\lambda A + B + \alpha_{OH} + \alpha_{IR}$$  \[3.12\]

where $A$, $B$, $\alpha_{OH}$, and $\alpha_{IR}$ are the Rayleigh scattering coefficient, the imperfection loss, and OH and infrared absorption losses, respectively. At the present time the losses in MOFs are dominated by OH-absorption loss and imperfection loss.

The OH-absorption loss in MOF is about 10 dB/km at 1380 nm. This causes an additional optical loss of 0.1 dB/km in the wavelength range around 1550 nm. Since this contribution is very similar to the intrinsic optical loss of 0.14 dB/km of pure silica glass at this wavelength, the OH-absorption loss reduction becomes important. Most of the OH impurities seem to penetrate the MOF core region during the fabrication process. As a consequence, a dehydration process is useful in reducing the OH-absorption loss.

Imperfection loss, caused mainly by air-hole surface roughness, is another area of concern in MOF manufacturing. During the fabrication process, the air-hole surfaces can be affected by small scratches and contamination. If this surface roughness is comparable with the considered wavelength, it can significantly increase the scattering loss. Hence it is necessary to improve the polishing and etching process, to effectively reduce the optical loss caused by this roughness. In
addition the fluctuations in the fibre diameter during the fibre drawing process can cause an additional imperfection loss, if the air-hole size and pitch change along the fibre. It is important to underline that the Rayleigh scattering coefficient of MOFs is the same as that of a conventional SMF. However, this is higher than that of a pure silica-core fibre, although the MOF is made of pure silica glass. It is necessary to reduce the roughness further, to obtain a lower imperfection loss and a lower Rayleigh scattering coefficient. It is fundamental to fabricate long MOFs with low loss, if they are to be used as transmission media.

Loss figures close to 0.28 dB/km are getting reported. The optical losses of these kinds of MOFs are still high compared with those of a conventional SMF. However, a solid-core MOF is not expected to have significantly lower losses than standard fibres.

Losses in hollow-core fibres are limited by the same mechanisms as in conventional fibres and in index-guiding MOFs. However, there is the possibility to reduce them below the levels found in conventional optical fibres, as majority of the light travels in the hollow core, where scattering and absorption could be very low. The major challenge lies in controlling the level of variations in the fibre structure along its length. The bandgap also presents a high sensitivity to structural fluctuations that occur over long fibre lengths. The wavelengths that are guided in one section may leak away in another.

The fibre nonuniformity can be reduced with a more careful fabrication process. It is impossible to eliminate the surface roughness due to Surface Capillary Waves (SCWs) frozen into the fibre when it is made. In fact, SCWs, which exist on liquid surfaces, like molten glass, where surface tension provides a restoring force, freeze as the glass solidifies, leaving a surface roughness given by the SCW amplitudes when the temperature equals the glass transition one. This roughness scatters light from the fundamental mode to the not guided ones, resulting in the fibre loss. It has been demonstrated that this surface roughness ultimately limits the hollow-core MOF attenuation. In fact, due to its thermodynamic origin, this roughness is not reduced with a better fibre drawing process.

Other technological improvements in homogeneity are likely to reduce the attenuation of hollow-core MOFs by not more than a factor of two. Moreover, the negative effect of the roughness can be decreased by a proper hollow-core fibre design that is by reducing the overlap
of the fundamental mode with the glass–air surfaces. By acting in these two directions, the hollow-core MOF attenuation can possibly be reduced from the actual record of 1.2 dB/km at 1620 nm to 0.2 dB/km at the same wavelength. In order to further reduce the attenuation, new fibre designs, new materials or a method for increasing surface tension are required.

### 3.9 Confinement Loss

Both solid-core and hollow-core MOFs are made from finite number of air holes in the fibre cross section. As a consequence, all the MOF guided modes are leaky. This gives rise to leakages or confinement losses. For example, in solid-core MOFs light is confined within a core region by the air-holes. Light will move away from the core if the confinement provided by the air-holes is inadequate. This means that it is important to design such aspects of the MOF structure as air-hole diameter and hole-to-hole spacing, or pitch, in order to realize low-loss MOFs. In particular, the ratio between the air-hole diameter and the pitch must be designed to be large enough to confine light into the core. On the other hand, a large value of the ratio makes the MOF multi-mode. However, by properly designing the structure, the confinement loss of single-mode MOFs can be reduced to a negligible level[^42].

![Fig 3.07 Leakage loss representation in a fibre cross section](image)

The cross section [inclusive of both defect and cladding] of MOFs is limited in practice and so the guided modes will leak out of the MOF. This confinement loss gives rise to small imaginary part $\beta$ in real fibres.
Several analyses performed have demonstrated a strong dependence of the confinement losses on the number of air-hole rings, for fibres particularly with high air-filling fraction. The leakage losses can be significantly reduced by increasing the ring number. The simulation results have also shown that in PBG fibres the leakage loss dependence on the number of air-hole rings is much weaker than in index-guiding MOFs.

In a MOF with an infinite number of air-holes in the photonic crystal cladding, the propagation is theoretically lossless. However, in the fabricated fibres the number of air-holes is finite, so the guided modes are leaky.

The primary contribution for loss in index guided MOFs are absorption and scattering like that of conventional optical fibres. However there are certain additional challenges also in respect of MOFs. The effective index of guided mode in air – silica fibre is well below that of Silica. Hence the mode tends to become leaky. This type of ‘confinement loss ‘ in photonic crystal fibres is dependent on the air filling fraction of the structure and number of holes present in the fibre structure.

For example, in solid-core MOFs light is confined within a core region by the air-holes. Light will move away from the core if the confinement provided by the air holes is inadequate. This means that it is important to design such aspects of the MOF structure as air hole diameter and hole-to-hole spacing or pitch in order to realize low-loss MOFs. In particular, the ratio between the air hole diameter and the pitch must be designed to be large enough to confine light into the core. Several analyses have been performed in order to find the guidelines to design both index guiding MOFs and PBG-based fibers with negligible leakage losses. In general this confinement loss can be reduced by increasing the period in structure.

In PBG fibres the leakage loss dependence on the number of air-hole rings is much weaker than in index guiding MOFs, whereas the confinement losses exhibit a strong dependence on the position of the localized state inside the PBG.
Fig 3.08 [a]. Leakage loss for various air fill fraction at 1.55 µm λ

Fig3.08 [a] shows the confinement loss [or leakage loss] as a function of pitch (Λ) for a range of different 4 ring MOF structures estimated\textsuperscript{[9, 25]}. Each curve represents results for a given fiber profile scaled to a range of different dimensions. We notice that the leakage loss always decreases when larger air holes are used because the mode is always more tightly confined to the core region for larger air-filling fractions, which is similar to the behaviour of step-index fibers.
Fig 3.08 [b]. Leakage loss for various rings at 1.55μm λ

Fig 3.08 [b] shows the confinement loss [leakage loss] versus Λ for a fixed air-filling fraction and different number of rings. For all the values of Λ, increasing the number of rings decreases the leakage loss because the holey cladding extends over a larger region. It is noted that the model generally underestimates the leakage loss. This is believed to be due to the fact that the openings between the holes, which are the main cause for the leakage of power, are replaced with closed rings.

The confinement loss CL of the mode is

\[ CL = 20α \log_{10} e = 8.686 \text{ Im} [k_0\text{neff}] \]  

[3.12]

Where \(k_0\) is the free space wave number and Im is the imaginary part.

3.10 Bending Loss

Conventional fibres suffer additional loss if bent more tightly than a certain critical radius. For wavelengths longer than a certain value, termed as” long wavelength bend loss edge” all guidance is effectively lost. The same behaviour is observed also in MOFs, which show additionally a “short-wavelength bend loss edge”, caused by bend-induced coupling from the fundamental to the higher order modes, which leak out of the core. In fact, at short wavelengths
the guided mode is mainly confined into the silica and when $\lambda \ll \Lambda$ the field can escape through the interstitial space between the neighbouring air-holes. As a consequence, the fibre becomes more sensitive to bending.

MOFs, with large air-filling fraction, that is a high $d/\Lambda$ value, exhibits a better resistance to the bending loss, whereas the hole-to-hole spacing $\Lambda$ roughly determines the position of the minimum of the bending loss curve, which roughly occurs at $\Lambda/2$. MOFs optimized for visible applications are more robust towards bending at any of the wavelengths from 400 to 1000 nm compared to a conventional fibre which is single-mode at the visible wavelengths [82].

MOFs with larger relative air-hole diameters, i.e. with higher $d/\Lambda$, are less sensitive to bending loss. However, the demand for single-mode operation and the need for large mode size limit the increase of $d/\Lambda$, and other solutions must be seen. It has been demonstrated that the bending losses [of triangular MOFs] can be improved by changing the air-hole configuration from the traditional single-rod core design. In particular, an alternative structure with the core region formed by three silica rods has been proposed, with the aim to improve the guided-mode area and the resistance to the bending loss, particularly at the short wavelengths. Numerical results have shown that, when the silica core is formed with three adjacent rods, the critical bending radius, defined as the radius at which the loss equals 3 dB/loop, can be reduced by approximately 20% with respect to the traditional single-rod MOF designs at 1064 nm, in excellent agreement with the experimental measurements.

In MOFs due to the complex nature of effective refractive index an accurate modelling of bending loss becomes more challenging. A theoretical model that successfully predicts the bending loss in LMA MOFs is already established. In that model the physical origin of the phenomenon is investigated, accounting for two different mechanisms that contribute to the overall loss, that is transition loss and pure bend loss.

The transition loss occurs where the curvature of the fibre changes suddenly, that is at the beginning or the end of the bend. This loss can be modeled as a sort of coupling loss, because the mode fields in the straight and curved sections are not aligned.

The pure bend loss is the continuous loss that occurs along any curved section of fibre, due to the inability of the tails of the field to keep in phase with the faster travelling central portion of the field. In this model, the full refractive index profile of the MOF is retained and hence the six
fold field shape as well. In fact, the bent fibre is modeled as a straight fibre with an equivalent index profile, given by a transformation that superimposes a gradient onto the refractive index of the straight fibre in the direction of the bend.

Other theoretical approaches have been developed, which provide a correct parametric dependence of the bending loss with the MOF geometric parameters. An analogy with the conventional step-index optical fibres has been applied, by introducing an effective normalized frequency for the MOFs, with an equivalent core radius and an effective refractive index for the microstructured cladding. Then, in order to describe the MOF bending loss, an expression for the power loss coefficient of the standard optical fibres due to the macro bending is considered.

It can be inferred hence that the macrobend loss depends on $\lambda$, $d$, and $\Lambda$. The critical radius $R_{\text{CR}}$ at which the loss is 3 db per loop is given by

$$R_{\text{CR}} = \frac{\Lambda^2}{\lambda^2}$$  \hspace{1cm} [3.13]

The cubic dependence on $\Lambda$ shows that critical radius increase rapidly with increasing mode areas while the inverse square dependence on wavelength explains the lower wavelength bend edge.

The bend losses can be decreased by increasing the number of cladding hole rings. Even though ESM MOF designs can be scaled to any arbitrarily large mode areas in practice bend loss sets the limit to maximum achievable area. In other words the usable bandwidth for single mode operation is limited by bend loss.

Hollow-core MOFs have different bending properties compared to Solid core ones. For applications like high-power delivery for medical use or material processing, which are suitable for air-guiding fibres, a low bending sensitivity is required, since it allows a very flexible use and an easy integration in supporting mechanical systems.

It is generally observed that no significant effect can be observed even by applying 10 turns with a small bending diameter of 4 cm. The most important effect obtained with bending is a shift of the short-wavelength bandgap edge towards longer wavelengths, thus causing a PBG
narrowing for the hollow-core MOFs. On the contrary, a similar shift has not been measured at the long-wavelength bandgap edge. In order to understand the fact that air-guiding MOFs are bending insensitive over most of the PBG, it is useful to consider the difference between the refractive index of the core, that is 1, and of the PBG edge, which corresponds to the cladding one. Being this difference very high that is about 2 x 10^{-2}, a very tight confinement of the guided-mode in the hollow-core can be obtained, which results in the robust guiding even through tightly bent MOFs.

As the transmission capacity increases FTTH [Fibre to the home] has drawn considerable attention. In FTTH systems the loss budget needs to be carefully controlled [79]. In other words the Fibre loss should be kept to the minimum. In a typical installation the fibre undergoes very sharp bends with radius as low as 10 mm or less. This essentially demands lower core size of the fibre and tight confinement of field within the core.

Photonic crystal fibre which has otherwise better bending losses compared to the conventional fibres attempt to meet the objectives by arrangement of hole sizes, rings and even doped core to increase core cladding refractive index contrast [80].

Fabrication is little involved in such technology. While the starting rod can be Germanium doped the capillaries need to be arranged surrounding it and heating and pressurization [time, temperature and pressure] need to be carefully controlled for achieving the desired profile.

Four such fibre cross section are shown below along with the parameters set and characteristics obtained. [Fig 3.09]

As it can be seen the refractive index difference between core and cladding increases as the holes sizes become bigger. The tight confinement leads to decrease in mode field diameter with increase in holes size. This increase in refractive index difference shifts cut off wavelength to longer wavelength.

Due to effective confinement the bending loss also decreases with increase in hole size. The splicing loss however needs to be handled with proper tapering when used in conjunction with conventional fibres [79].
Fig 3.09 SEM image of 4 fibres with various d/Λ ratios [Courtesy photonic research centre]

<table>
<thead>
<tr>
<th></th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
<th>Sample 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core dia µm</td>
<td>8.7</td>
<td>8.7</td>
<td>8.7</td>
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<tr>
<td>Cladding dia µm</td>
<td>125</td>
<td>125</td>
<td>125</td>
<td>125</td>
</tr>
<tr>
<td>Hole dia µm</td>
<td>9.1</td>
<td>13.6</td>
<td>17.4</td>
<td>24.4</td>
</tr>
<tr>
<td>Pitch µm</td>
<td>19.2</td>
<td>20.7</td>
<td>23</td>
<td>27.5</td>
</tr>
<tr>
<td>Cut of λ µm</td>
<td>1188</td>
<td>1192</td>
<td>1264</td>
<td>1292</td>
</tr>
<tr>
<td>Mode field dia µm</td>
<td>10.34</td>
<td>9.98</td>
<td>8.69</td>
<td>5.63</td>
</tr>
<tr>
<td>Dispersion ps/nm.km at 1550 nm</td>
<td>18.45</td>
<td>18.52</td>
<td>18.9</td>
<td>19.83</td>
</tr>
<tr>
<td>Bending loss DB/turn At 1550 nm</td>
<td>A] 7.5mm radius</td>
<td>0.02</td>
<td>0.01</td>
<td>0.009</td>
</tr>
<tr>
<td></td>
<td>B] 5.0 mm radius</td>
<td>0.44</td>
<td>0.06</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>C] 2.5mm radius</td>
<td>9.42</td>
<td>4.32</td>
<td>1.42</td>
</tr>
</tbody>
</table>

Table 3.3 Calculated values of sample fibres
3.11 Dispersion

Material dispersion refers to the wavelength dependence of the refractive index of material caused by the interaction between the light and ions, molecules or electrons in material. Apart from material dispersion, another important dispersion type in optical fibers is waveguide dispersion. Waveguide dispersion depends among others on the core diameter and on the refractive index contrast between the core and the cladding. Generally, conventional optical fibers have dispersion characteristics close to the material dispersion of silica due to their small waveguide dispersion resulting from a low index contrast between the core and the cladding.

In contrast, MOFs offer new possibilities for dispersion control due to their tailorable waveguide dispersion [13]. The dispersion profile of MOFs can be tuned by changing the pitch (Λ) and the air-hole size (d). The effect of waveguide dispersion is particularly strong for MOFs with a high air-filling fraction (d/Λ) and small dimensions. By properly choosing the structural parameters, the zero-dispersion wavelength (\(\lambda_{ZD}\)) can be shifted from the near infrared to visible wavelengths. It is also possible to obtain very high dispersion values which are of interest in dispersion compensation as well as nearly flat dispersion profiles with low dispersion values. By suitably infiltrating the holes with liquids or liquid crystals as another freedom of choice dispersion characteristics can be further altered.

Light can propagate in optical fibres in the allowed modes which are the field distributions described mathematically by the solutions to the Maxwell equations. The number of allowed modes and the intensity distribution is governed by the parameters of optical fibre. The propagation constant \(\beta\) for a particular mode travelling in an optical fibre is the component of wave vector \(k\) parallel to the core cladding boundary and governs how the phase of the mode varies with the distance. It is conserved at the boundaries parallel to the propagation. The allowed values of \(\beta\) are governed by core, cladding refractive indices.

\[
    n_{cl}k_0 < \beta < n_{co}k_0
\]  

[3.14]

where \(n_{cl}\) and \(n_{co}\) are the refractive indices of cladding and core respectively. \(k_0\) is the free space wave vector given by \(2\pi/\lambda\).
We can define effective refractive index for a mode with a propagation constant $\beta$ as

$$n = \beta/k_0 \quad [3.15]$$

$\beta$ depends on $n$ which itself is a function of frequency so the individual frequency components of a pulse will have different propagation constants and travel at different velocities leading to chromatic dispersion. Chromatic dispersion governs how the pulse width and intensity evolve along the fibre length.

Fibre dispersion is of critical importance for the propagation of ultra short pulses as various spectral components associated with pulse travel at different speeds. Taylor series expansion is applied to $\beta$ around angular frequency $\omega_0$ to express the effects of dispersion.

$$\beta(\omega) = n_{\text{eff}}(\omega) = \beta_0 + \beta_1(\omega-\omega_0) + \frac{1}{2} \beta_2 (\omega-\omega_0)^2 + \frac{1}{6} \beta_3 (\omega-\omega_0)^3 + \quad [3.16]$$

Where $\beta_m = \left. \frac{d^m \beta}{d \omega^m} \right|_{\omega=\omega_0} \quad [3.17]$

The coefficients $\beta_1$ and $\beta_2$ are related to the refractive index and its derivatives.

$$\beta_1 = \frac{1}{v_g} = \frac{n_g}{c} = \frac{1}{c} \left[ n + \omega \left. \frac{dn}{d\omega} \right| \right] \quad [3.18]$$

$$\beta_2 = \frac{1}{c} \left[ 2 \left. \frac{dn}{d\omega} + \omega \left. \frac{d^2 n}{d\omega^2} \right| \right] \quad [3.19]$$

where $v_g$ is the group velocity and $n_g$ is the group index. The parameter $n_g$ varies as a function of $n$ as given by

$$n_g = n(\lambda) - \lambda \left. \frac{dn(\lambda)}{d\lambda} \right/ \lambda \quad [3.20]$$

$\beta_1 = 1/v_g$ where $v_g$ is the group velocity. The envelop of the pulse moves with the group velocity.

$\beta_2$ = the dispersion of group velocity and responsible for pulse broadening and its unit is $\text{ps}^2\text{km}^{-1}$.

$B_3$ = Third Order Dispersion [TOD] coefficient and its inclusion is necessary when the pulse wavelength approaches the zero GVD point.
It is more common and comfortable to work with wavelength rather than frequency domain. Hence the group velocity dispersion [GVD] $\beta_2$ and dispersion parameter $D$ are related by,

$$D \text{ [ps/nm/km]} = -\frac{\lambda}{e} \frac{d^2}{d\lambda^2} \{\text{Re} \{n_{\text{eff}}\}\} = -\frac{2\pi e}{\lambda^2} \beta_2 \quad [3.21]$$

If parameter $D$ is negative, that dispersion regime is normal and red components of pulse travel faster than the blue components. The frequency chirp will be positive. When $D$ is positive the dispersion region is anomalous and red components of pulse travel slower than the blue components. The frequency chirp will be negative.

When $D = 0$ all components of pulse travel at the same speed as this corresponds to zero dispersion wavelength. When $D$ is zero pulse maintains its shape and when $D \neq 0$ the pulse spreads in time. The dispersion parameter as a function of wavelength can be also written as

$$D (\lambda) = D_0 + S (\lambda - \lambda_0) + \frac{T}{2} (\lambda - \lambda_0)^2 + \frac{F}{6} (\lambda - \lambda_0)^3 \quad [3.22]$$

where $D_0$, $S$, $T$ and $F$ are the dispersion (at $\lambda_0$), dispersion slope, third order dispersion and fourth order dispersion, respectively. The $\lambda_0$ parameter is the reference wavelength around which $D (\lambda)$ is expanded.

![Graph showing variation of $D$ and $\beta_2$ with wavelength for bulk silica](image.png)

Fig 3.10. Variation of $D$ and $\beta_2$ with wavelength for bulk silica
For a pulse of a given duration propagating in a fibre a characteristic length can be defined over which the dispersion effects become important. This length $L_D$ is defined as the dispersion length and is given by

$$L_D = \frac{\pi^2}{\beta_2}$$  \hspace{1cm} [3.23]

It can be inferred that dispersion becomes important for shorter pulses. This is due to the broader band width of a shorter pulse. The dispersion parameter $D$ in the unit of ps/ km/ nm is commonly used instead of $\beta_2$.

There are two contributions to the overall dispersion of optical fibres namely [a] material dispersion and [b] waveguide dispersion. Material dispersion is the intrinsic dispersion of a bulk medium arising from the interaction between an electromagnetic wave and the electrons in the medium. The proximity in wavelength of the electromagnetic wave to the electronic resonances of the medium affects the response of the medium. It is this which accounts for the wavelength dependence of the refractive index in bulk media.

Apart from the contribution to the dispersion from the bulk material, there is also a waveguide contribution to the dispersion arising from the confinement of optical waves. Waveguide dispersion arises as the effective mode index of the dielectric waveguiding is wavelength dependent as well. The waveguide dispersion contribution hence can easily be manipulated. Changing the core size and the refractive index difference between the core and cladding can evidently change the waveguide dispersion.

For conventional optical fibres which have a core-cladding index contrast of only 1-2% there is only a slight modification from the bulk silica dispersion curve, although introducing rings of different dopants around the core and tapering the fibre can be used to adjust the slope and position of the zero dispersion wavelength. As MOFs have a large core-cladding index contrast, the contribution from the waveguide dispersion can be quite large, significantly altering the overall dispersion from that of the bulk material.

The effective refractive index of MOF cladding structures can be approximately varied anywhere between that of silica and that of air by changing the size and separation of the air holes. The unique dispersion properties of MOFs arise from the highly controllable waveguide dispersion. In conventional fibres the parameters to be adjusted are limited. For MOFs,
however, the control of dispersion is more flexible and easier. By adjusting the size of the hole-to-hole pitch, $\Lambda$, and the hole diameter, $d$, one can control the air filling ratio easily to change the core-cladding index difference and the core size so that desired dispersion is achieved\textsuperscript{[26]}. In addition the option of infiltrating the holes also is available.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3_11.png}
\caption{Calculated GVD for fixed core dia and various $d/\Lambda$ ratios}
\end{figure}

The figure 3.11 shows that the Zero-Dispersion Wavelength (ZDW) of a MOF can be shifted to the wavelengths shorter than 1.27 μm, the ZDW of bulk silica\textsuperscript{[14]}. When the holes get bigger, the ZDW is shifted to further shorter wavelengths. However, the ZDW shift becomes slower with the increasing of $d/\Lambda$. This can be understood from the fact that the ZDW shift is due to the large waveguide dispersion contribution to the total GVD. Large air holes increase the core-cladding index step resulting in a large anomalous waveguide dispersion, which can cancel the normal material dispersion at $\lambda < 1.27 \ \mu m$ or even overcome it to yield anomalous net dispersion there. However, when the holes get big enough ($d/\Lambda =0.95$, for example), making the holes further bigger will not bring significant change to the core-cladding index step. Hence the
waveguide dispersion introduced by big holes cannot further change the overall GVD. In case the ZDW of MOFs is to be shifted to even shorter wavelengths, the option of altering the fibre core diameter is to been.

![Graph showing calculated GVD for fixed d/\(\Lambda\) and variable core size](image)

**Fig3.12. Calculated GVD for fixed d/\(\Lambda\) and variable core size**

In order to study how the GVD of MOFs varies with the fibre core diameter \(d_{\text{core}}\), the GVD curves of the fundamental mode are calculated for MOFs with different core diameters but having a fixed \(d/\Lambda\) and plotted in Fig.3.12\(^{[14]}\). It can be seen that when \(d/\Lambda\) is fixed, decreasing \(d_{\text{core}}\) can also shift the ZDW to shorter wavelengths. This is because when fibre core becomes smaller whilst core-cladding index difference keeps constant, the \(V_{\text{eff}}\) will be smaller. As a result, the fibre mode will expand more into the cladding. This will lead to large anomalous waveguide dispersion at \(\lambda< 1.27 \mu\text{m}\) as well. However, when \(d/\Lambda\) is not very big, \(d/\Lambda = 0.4\), for example, simply decreasing \(d_{\text{core}}\) cannot shift the ZDW further once \(d_{\text{core}} < 3 \mu\text{m}\). Instead, a second ZDW appears at a longer wavelength. If we want to achieve an even shorter ZDW, we need to increase \(d/\Lambda\) when decreasing \(d_{\text{core}}\). Figure shows that the ZDW can be as short as 680
nm when $d/\Lambda = 0.8$ and $d_{\text{core}} = 1.5 \, \mu\text{m}$. Such MOFs with high $d/\Lambda$ and small $d_{\text{core}}$ are normally referred to as highly nonlinear MOFs.

### 3.12 Birefringence and Polarization Mode Dispersion

Birefringence in optical fibers results from small variations in the cylindrical symmetry of the fiber and from asymmetrical stress distribution. Due to the local fluctuations in the core shape and stress distribution in the fiber, birefringence changes randomly along the fiber. This phenomenon is commonly referred to as polarization-mode dispersion and can limit the data transmission in long distance high bit-rate communication systems.

The large refractive index contrast of MOFs enables high form birefringence whereas the unique manufacturing process gives a precise control over the cross-sectional index profile. The birefringence in MOFs is usually based on the asymmetrical shape of the core or the cladding microstructure and birefringence of more than an order of magnitude higher compared with conventional optical fibers has been reported. Moreover, the birefringence in MOFs is robust against temperature variations due to the single fabrication material. This unique property can be exploited in, e.g., gyroscopes, interferometers and polarimetric sensors. Furthermore, it is possible to induce stress birefringence in MOFs, which allows for the realization of polarization-maintaining single-mode large-mode area fibers.

### 3.13 Nonlinearity

The manufacturing process of MOFs allows for the fabrication of fibers with a very small core diameter ($\sim 1-2 \, \mu\text{m}$) and a high air-filling fraction. Consequently, the propagating modes can exhibit very small effective mode areas compared with conventional fibers. As the magnitude of the nonlinear coefficient is inversely proportional to the mode area, narrow-core MOFs can exhibit high nonlinearities. The high nonlinearity combined with the special dispersion properties of MOFs provides new possibilities in nonlinear optics. Furthermore, the mode area of MOFs can be wavelength dependent. This can be exploited in the realization of wavelength dependent nonlinear effects.
3.14 Chapter Summary

In order to simply design a MOF, the empirical relations for both $V$ parameter and $W$ parameter of MOFs dependent only on the air hole diameter and the hole pitch were studied as presented above. The method is fairly accurate when compared with the results of numerical methods like full-vector FEM taken for reference. Through the empirical relations the fundamental properties of MOFs could be easily understood without the need for numerical computations. Certain basics and unique characteristics also discussed in this chapter. The following points are noteworthy.

1. It is possible to have high numerical aperture of the order of 0.6, 0.7 or even up to 0.9

2. Single mode guidance can stretch across wide wavelengths and endlessly single mode operation is possible for small hole and pitch ratios. Band expansion is hence possible.

3. Extremely large or small mode area fibres can be made with small numerical aperture like conventional fibres. Weak or strong nonlinearities and low bend loss characteristics hence can accordingly be obtained.

4. Certain hole arrangements can create photonic band gaps and such fibres are called photonic band gap fibres. Such structures can help in wavelength segregation. Guidance is possible in such hollow core fibres. Hollow core will aid in high power pulse compression etc. Liquid filling is also possible in such fibres. Liquid filled fibres are helpful in sensing applications.

5. Asymmetrical hole fibres will be useful in maintaining polarization.

6. Very unusual properties like anomalous dispersion in visible region are possible with microstructured optical fibres.

The curves of $V$ parameter, $W$ parameters etc are generated in Matlab version 7.5. Matlab codes written are also enclosed.